Istituto Nazionale di Fisica Nucleare
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A. Bertin: NUCLEAR CAPTURE OF NEGATIVE MUONS IN GASEOUS HYDROGEN: PRESENT STATUS OF THE EXPERIMENT.(o)

1. - INTRODUCTION. -

The measurements which I am going to discuss have been performed in collaboration between the Bologna University and CERN(x), with the aim of determining the nuclear capture rate of a μ^- meson by a proton, when the process

$$(1) \qquad \mu^- + p \rightarrow n + \nu_\mu$$

is observed in a target of gaseous hydrogen.

The rate of reaction (1) is foreseen in the frame of the present theory of weak interactions; and the result of an experiment which produces this value has to be considered among the most interesting tests of the (V - A) form of these interactions. Furthermore, such a measurement yields a datum on the still uncertain value of the constant g_p, which describes the pseudoscalar coupling induced in weak processes when particles with a strong structure are also involved (see Appendix).

(o) - Text of a lecture held in Bologna, during the Seminari Bolognesi di Fisica Sperimentale, March 20-22nd 1967.

(x) - A. Alberigi Quaranta, A. Bertin, G. Matone, F. Palmonari and A. Placci (Bologna); and P. Dalpiaz, G. Torelli and E. Zavattini (CERN). The experiments have been performed at CERN, using the muon channel of the 600 MeV synchrocyclotron[1].

In order to clear up the general features of the problem, and mainly the peculiar requirements which have determined the choice of the method, let us briefly recall the possible ways of interaction of a negative muon with matter, and in particular with a hydrogen target.

1.1 - When a beam of negative muons of low energy (some tens of MeV, for instance) impinges against a solid target constitued by an element Y, the situation is the one sketched in Fig. 1, i. e.

a) the μ^-'s may decay following the process

$$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu \tag{2}$$

with a mean lifetime τ = 2.2 microsec (that means at a rate $\lambda_o = 1/\tau$ = =4.45 10^5 sec^{-1});

b) while crossing the target, the muons lose their energy by ionization; in this way, within a time very short in comparison to their mean lifetime, their energies attain values which are low enough in order that they may be captured by a Y atom in an excited level of the atomic system μY. Such a system, known as a mesic atom, is formed due to the electrostatic attraction between the μ^- and the nucleus of Y, and to the relatively long muon lifetime. It decays promptly (i. e. within 10^{-10} sec) to its ground state, by emission of a series of gamma radiations, which are characteristic of the considered element Y;

c) in the mesic atom μY, the muon may either decay following process (2) (at a rate λ_{dY}), or be captured by the nucleus of Y, by a process analogous to (1), and accompanied by the emission of one or more neutrons. This is due to the fact that, since the Bohr orbits of the mesic atoms have dimensions which are reduced, in comparison to the electronic orbits, by a factor of the order of m_μ/m_e = 200, the wave function of the muon overlaps to the nucleus in an exceptional way.

It has besides to be underlined that the nuclear capture rate λ_{cY} for negative muons increases with the atomic number Z of the capturing nucleus Y approximately as fast as Z^4 (2). Therefore, whereas the latest theoretical predictions give a value of 626 sec^{-1} for the rate of process (1) - when this takes place in a μp atom in the singlet state of the hyperfine structure -, the rates corresponding to the nuclear capture of the muon in oxygen (Z = 8) and in iron (Z = 26) are respectively larger by a factor about 100 and 10000 (see Table I).

1.2. - If now the mesic atoms are formed in a liquid (or gaseous) hydrogen target, they are born in a statistical mixture of triplet and singlet spin states, in each of which process (1) can take place. Furthermore, as it is drawn in Fig. 2, the peculiar properties of the μp mesoatom and the fluidity of the medium open some new channels in comparison to the situation of Fig. 1. The μp systems, in fact, are not

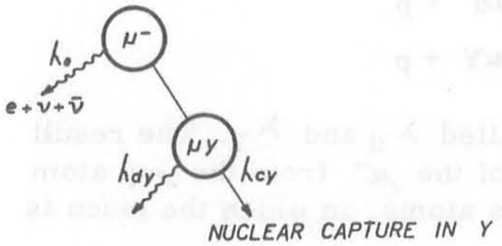

FIG. 1 - Negative muons slowing down in a solid target.

only electrically neutral, but they also have very little dimensions in comparison to the ordinary atomic dimensions: the Bohr radius of the μp system is actually $r_{\mu p} = \hbar^2/m_{\mu} e^2 = 2.56\ 10^{-11}$ cm. Their behaviour as a whole is therefore similar to the one of slow neutrons[3]. They diffuse throughout the hydrogen, scattering against the atoms of such a medium, and rapidly leaving the triplet states to populate the lower energy singlet states. During the diffusion, the following processes compete:

a) the formation of a pμp ion: i.e. the μp system may get bound to a further hydrogen atom, according to the reaction

(3) $$\mu p + p \rightarrow p\mu p$$

(which proceeds at a rate λ_{pp}) thus constituting a molecular ion, in which process (1) may take place at a rate λ_{mol}.

b) the transfer process of the μ^- to impurity atoms: the electrical neutrality of the μp systems allows them to arrive in proximity of the nuclei of other atoms, without feeling in a critical way the electrostatic action due to orbital electrons and nuclei. If in the hydrogen some deuterium atoms are present, or even atoms of elements Y the atomic number of which is larger than 1, the two reactions

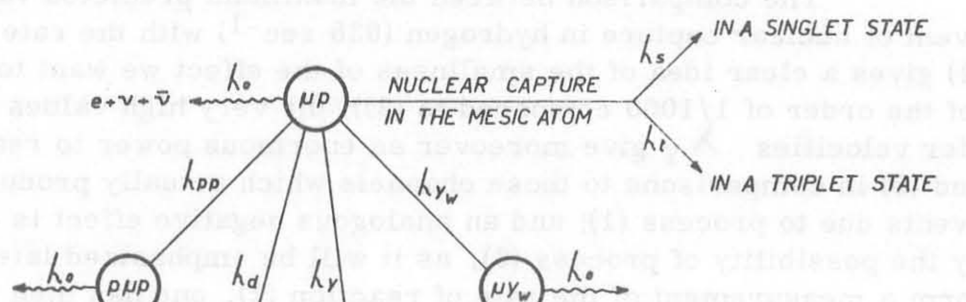

FIG. 2 - Negative muons slowing down in a hydrogen target

(4) $\mu p + d \rightarrow \mu d + p$

(5) $\mu p + Y \rightarrow \mu Y + p$

can take place, at rates respectively called λ_d and λ_Y. The result of both these processes is the transfer of the μ^- from the μp atom to a mesic orbit of one of the extraneous atoms, in which the muon is more tightly bound;

c) the transfer process of the μ^- to the walls of the container: while diffusing throughout the hydrogen, the μp atom may attain the walls of the container, where, (let the wall be made of an element Y_W) the reaction

(6) $\mu p + Y_W \rightarrow \mu Y_W + p$

is allowed for the same reasons treated in b), and proceeds at a rate λ_W.

Reactions (4), (5) and (6) are irreversible, and, once they have been produced, the nuclear capture process in the elements d, Y, Y_W takes place, at a rate competing with the one of the decay (2) in a way which increases (as it has been told) approximately with the fourth power of the atomic number of the capturing nucleus.

In Table I the rates of the main described processes are listed, and they are compared with the theoretical predictions for the rate at which reaction (1) proceeds, in the atomic and molecular systems of Fig. 2.

The comparison between the maximum predicted value for an event of nuclear capture in hydrogen (636 sec^{-1}) with the rate of process (2) gives a clear idea of the smallness of the effect we want to observe (of the order of 1/1000 compared to (2)); the very high values of the transfer velocities λ_Y give moreover an enormous power to reactions (4) and (5) in comparisons to those channels which actually produce some events due to process (1); and an analogous negative effect is generated by the possibility of process (6), as it will be emphasized later. To perform a measurement of the rate of reaction (1), one has then to keep the following criteria:

a) to get a clear knowledge of the state of the system from which the reaction proceeds: it is important to know wether this is a molecular, or an atomic state, and in the latter case which is the hyperfine structure state which the mesic atom occupies when the capture takes place.

b) to prepare the detection of the phenomenon in such a way to eliminate (or in any case to reduce to negligible effects) the competing reactions sketched in Fig. 2

TABLE I

PROCESS	RATE (sec^{-1})
Muon decay (react. (2))	$\lambda_o = 4.45\ 10^5$
μ^- capture in hydrogen (react. (1), theoretical predictions)	
a) μp singlet	$\lambda_s = 636 \pm 5\%^{(2)}$; $626 \pm 1\%^{(4)}$
b) μp triplet	$\lambda_t = 13 \pm 5\%^{(2)}$; $12 \pm 1\%^{(4)}$
c) pμp ion	$\lambda_{mol} = 560.$ (5); $477 \pm 4\%^{(4)}$
pμp molecular ion formation (react. (3))	$\lambda_{pp} = 2\ 10^6$ (6, 7, 8)(+)
Transfer processes to Z > 1 nuclei and to deuterium (react. (4, 5, 6))	$\lambda_Y = 10^{10} \div 10^{11}$ (+)
μ^- nucl. capture in oxygen	$\lambda_{c0} = 9.7\ 10^{4}$ (5)
μ^- nucl. capture in iron	$\lambda_{cFe} = 4.53\ 10^{6}$ (5)

1.3. - The experiments up to 1964 have been all performed by use of liquid hydrogen targets; at such density, due to the high value for λ_{pp}, one has a huge formation of molecular ions (pμp), and the nuclear captures proceed mainly from such systems. The results obtained for λ_{mol} in these experiments are listed in Table II.

TABLE II

Experimental Team	Technique	λ_{mol} (sec-1)
CERN - Bologna(9)	Bubble chamber	450 ± 50
Chicago(10)	Bubble chamber	428 ± 85
Columbia(11)	Counters	464 ± 42

The experiments of the CERN - Bologna collaboration, and the Chicago experiment have been performed by photographing negative muons stopped in the liquid hydrogen of a bubble chamber: the μ^-'s were recognized by the residual range and by the bending of their tracks under the action of the magnetic field; and the events of nuclear capture were identified by the lack of the decay electron, and the presence, at a

(+) - Values referred to the density of liquid hydrogen.

certain distance from the point in which the muon had stopped, of a recoil proton the energy and the direction of which could be attributed to a neutron coming from process (1).

The Columbia experiment, on the contrary, has been based on the technique of detecting (by a counters arrangement) the neutrons in time correspondence with the stopping of negative muons in hydrogen.

As it can be seen in Table I, the values obtained in these results are in reasonably good agreement between them; but, since the value which theory had proposed for λ_{mol} was 560 sec^{-1} up to the end of these experiments, the idea of a possible discrepancy between the theoretical predictions and the experimental results was considered. Then, since the value for λ_{mol} is actually given by

$$\lambda_{mol} = 2 \gamma (3/4 \lambda_s + 1/4 \lambda_t) \tag{7}$$

where γ is a factor which is due to the molecular character of the phenomenon, and has to be evaluated theoretically, it was suggested (and later confirmed by more precise calculations[4]) that the discrepancy could be attributed to the error in the calculation of γ ; and that, in order to yield a number which might be more reliably compared to the predictions, reaction (1) ought to be produced in a system free from molecular complications, so that the result of the measurement would be only one of the two parameters λ_s and λ_t.

The only way of satisfying these requirements is just that of observing reaction (1) in a target of hydrogen at such a low density ρ_H that the molecular ion formation (which proceeds now at a rate[(x)] $((\rho_H / \rho_{Hliq}) \lambda_{pp})$ is inhibited; and it can be shown that the nuclear captures in the $p\mu p$ ions becomes a known fraction, and less than 10%, of the analogous events due to the nuclear captures in the mesic atoms, if negative muons slow down in a target of gaseous hydrogen at a pressure around 10 abs. atm.

2. - THE TECHNIQUE AND THE PRELIMINARY MEASUREMENTS. -

The choice of the method we adopted to measure the rate of reaction (1) in gaseous hydrogen has been directed towards counters techniques. In analogy to the experiment executed by the Columbia group in liquid hydrogen, a group of counters properly situated defines the μ^- stopping in the target; this event opens a gate for a fixed time interval (Δ t), which interrogates the assembly of another group of counters (N_i); these ones encircle the target, and are specially constructed to detect neutrons. If, during the time Δt, one of the N_i counters detects a neutron, one has got what is called an event, i. e. a neutron correlated with the stopping of the μ^- which has opened the gate; and, as it will be

(x) - ρ_{Hliq} being the liquid hydrogen density.

seen in detail later, one obtains the measurement of the rate of reaction (1) just counting the number of these events, and comparing it with the whole number of muons correspondingly stopped in hydrogen.

From what has been said while discussing the situation sketched in Fig. 2, it is clear that the neutrons (which have been in this way identified as events) may be attributed to process (1) only if one has taken care of switching off all the processes which compete with it; and that, to analyse the data, it is essential to know the spin state of the atomic system in which the capture is produced. The fulfilment of these requirements, all of them preparatory to the chief experiment, has imposed the necessity of some preliminary measurements, and the setting up of an unusual technique, which I am going to discuss in what follows.

2. 1. - The purification of the gas. - It has previously been stated that the $p\mu p$ molecular ion formation (reaction (3)) can be strongly inhibited by slowing down negative muons in gaseous hydrogen at a pressure of the order of 10 atm. The problem is now to close all the other channels which could yield capture neutrons due to nuclei different from hydrogen.

The elimination of transfer processes to deuterium atoms (reac. (4)) has been obtained by using a special type of hydrogen (protonium), industrially produced[(o)], which contains less than 3 p. p. m. of deuterium; since the μ^- nuclear capture rate in deuterium[(12)] is of the same order of magnitude as the rate of nuclear capture in hydrogen, this channel is definitively forbidden.

Furthermore, for a system of mesic atoms formed in these conditions, the residual channels of Fig. 2 (apart from react. (6)) have a flow respectively proportional to the numbers

$$\lambda_o, \ (\rho_H / \rho_{Hliq}) \lambda_{pp}, \ (\rho_H / \rho_{Hliq}) c_Y \lambda_Y,$$

where c_Y is the concentration of an extraneous element Y in the protonium; it is then possible to act on c_Y to stop reaction (5): once the transfer velocities λ_Y are known, it is easy to determine the maximum tolerable concentration c_Y of the element Y in the protonium, in order that the corresponding background effect be made sufficiently small in the experiment.

No satisfactory measurements of the λ_Y rates were available when we stated our problem; a preliminary experiment was there-

(o) - The supplying firm is Air Liquide, Paris, France.

fore performed at CERN[13] to measure such parameters in correspondence of a certain number of elements Y. Negative muons were slowed down in a target of gaseous hydrogen to which known proportions of the element Y had been added. The technique consisted mainly in observing the time distribution of the gamma rays (characteristic of the mesic atom μY) emitted during the de-excitation process which follows reaction (5). From this time distribution, characterized by a mean lifetime τ such that

(8) $$1/\tau = \lambda_o + \rho_H/\rho_{Hliq} \left(\lambda_{pp} + c_Y \lambda_Y \right)$$

it is easy to calculate λ_Y.

Monoatomic elements Y have been chosen for the experiment, in order that the produced reactions might be as simple and as similar to react. (5) as possible; the choice has besides been fixed on noble gases, since these cover a large interval of atomic numbers Z, and the theory[14] foresees a dependence of λ_Y from Z which we wanted to check.

The obtained results are shown in Fig. 3, together with those which another team published (while our experiment was running) on some of the Y elements which we considered, and exploiting a different technique. Some theoretical predictions are also quoted in the figure.

The conclusions one draws from this evidence establish that the degree of purity of the protonium is an extremely critical parameter: less than 1 p.p.m. of gaseous impurities are actually tolerable if one wants to confine the background due to the consequences of reaction (5) within tolerable limits.

The safest way to satisfy this requirement is to purify the protonium by a palladium filter[o], which warrants in the purified gas less than 10^{-2} p.p.m. of residual impurities. This solution obviously implies particular refinements in the realization and in the mounting of the container for the gas, which must be high-vacuum tight (up to 10^{-6} mm Hg) and easy to be degassed.

The high value of the transfer rate λ_y in the case of xenon has suggested a method to measure, during the main experiment, the background neutrons due to those μ^-'s stopping in any light material present in the container for necessity of construction. Due to the low atomic number Z of these materials, the neutrons due to nuclear capture in light elements - as it has been said concluding 1.1 - are emitted with a long mean lifetime ($\lambda_{cC} = 0.394\ 10^5\ sec^{-1}$ in carbon, for

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(o) - The supplying firm is Engelhard Industries , Newark, N. J., USA.

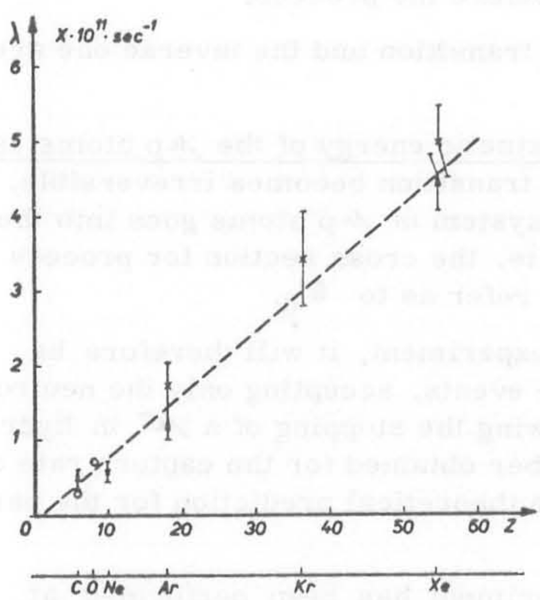

FIG. 3 - Theoretical and experimental values for the transfer rates of negative muons from μ p atoms to heavier nuclei.

x Alberigi et al.[13]

▲ Basiladze et al.[15]

o Theoretical predictions[14]

instance[5]); therefore, they cannot be eliminated by a time cut at times shorter than $1/\lambda_0$, which is the reference time as to the disappearence of muons. A measurement of this background is however possible, if within a short time all the muons, which have formed mesic atoms μ p, may be conveyed on other high-Z atoms, which yield prompt capture neutrons. It is actually easy to see, using the parameters (8), that if the purified protonium is contaminated by a 1/1000 proportion of xenon (which does not affect in a noticeable way the stopping power of the protonium), the mean requested time in order that the transfer process (5) to the xenon atoms happen is about 200 nanosec; remembering that, on the average, the nuclear capture of the muon in a μ Xe atom proceeds in an even shorter time, one gets that, after approximately 1 microsec., all the neutrons detected by the apparatus are certainly not due to μ^- capture in hydrogen; and the experimental conditions have not been affected.

2. 2. - The determination of the initial hyperfine structure state. - As it has been told in 1. 2, the system of mesic atoms, which is formed when a beam of negative muons is slowed down in hydrogen, is initially in a statistical mixture of triplet and singlet spin states. In our case, the mesic atoms diffuse throughout the gas, scattering against its atoms and undergoing some energy exchanges with them. The result of these exchanges is that the kinetic energy of the mesic atoms, from an initial value of about 1 eV, rapidly degrades towards the thermal value (0. 03 eV at 300° K).

Furthermore, as long as their kinetic energy is larger than the energy difference ΔE between the triplet and the singlet state of the hyperfine structure ($\Delta E = 0.18$ eV), the scattering reaction

(9) $$\mu p + p \rightarrow \mu p + p$$

(which is described by a cross section which we shall call $\sigma_{1,0}$) proceeds in such conditions that:

- after each scattering, the spin state of the μp atom may either be changed or be the same as before the process;

- both the triplet → singlet transition and the inverse one are allowed.

On the contrary, when the kinetic energy of the μp atoms is lower than ΔE, the triplet → singlet transition becomes irreversible, and within a certain time $\bar{t}$ the whole system of μp atoms goes into the lower energy singlet state; in this state, the cross section for process (9) has a different value, to which we refer as to σ_0.

As to the data of the main experiment, it will therefore be sufficient to operate a time cut on the events, accepting only the neutrons detected after a time equal to $\bar{t}$ following the stopping of a μ^- in hydrogen, in order to be sure that the number obtained for the capture rate of reaction (1) has to be compared to the theoretical prediction for the parameter λ_s.

A second preliminary experiment has been performed at CERN(16) with a view to determining $\bar{t}$; the technique has been based on the exceptional circumstance that the cross section for process (9) depends in a "resonant" way on the band of energies in which the mesic atom moves; more precisely, the theory(3, 17) foresees for $\sigma_{1,0}$ a value of the order of some 10^{-19} cm^2, whereas for σ_0 a number of the order of magnitude of 10^{-21} cm^2. A determination of the scattering cross section for process (9), and occasionally of the time interval after which its value decreases by almost two orders of magnitude has therefore to supply the requested information.

The measurement of the cross section for process (9) has been reduced essentially to the measurement of the mean free path of the mesic atoms μp, which has been determined by measuring the time distribution of the μp systems which, after having been formed in gaseous hydrogen, attain the surface of foil made of a high-Z element, dipped in the gas itself. As in the first measurement discussed in 2.1, the arrival of the μp mesoatom to the surface of the foil, and the quick transfer of the muon from the μp atom to the extraneous high-Z element has been identified by detecting the characteristic gamma radiation emitted during the deexcitation of the new mesic atom.

The first result of the measurement has been to show that, starting from an initial energy of about 0.5 eV, the μp atoms go definitively in the singlet state within a time of about 30 nanosec. A time cut of this order of magnitude is then actually sufficient to be sure that the collected events are to be attributed to nuclear captures in mesic atoms and in the singlet state of their hyperfine structure. It is interesting to notice that our results, among which only σ_0 is listed in Table III for sake of brevity, are in disagreement with those obtained by another team(18) in some preceeding measurements, which were performed by a technique in which the phenomena was observed in hydrogen not completely purified by the presence of other elements.

TABLE III

Authors	$\sigma_0 \times 10^{21}$ cm^2
Alberigi Quaranta et al. (16)	7.6 ± 0.7
Dzhelepov et al. (18)	167 ± 30
Zel'dovich and Gershtein (3) } (theoretical predictions)	{ 1.2
Cohen et al. (17)	8.2

2.3. - The necessity of keeping the gas in a container "without walls". - The last competing channel of Fig. 2 which following this discussion has not yet been cut off is the one corresponding to the diffusion of the μp system up to the walls of the container, with a subsequent reaction (6), and nuclear capture of the muon in the heavy element Y_W, i. e., production of a background of delayed neutrons. Another result of the experiment described in 2.2 has been the fact of allowing a precise determination of the danger coming from this channel, which can be obtained starting from the results got for the mean free path of the μp atoms subject do process (9). It can actually be shown that, if R is the ratio between the number of μ p atoms which are transferred to the wall of the container after a time t_o, and the number of muons which decay after time t_o (under the hypothesis that muons are uniformely stopped in a container the diameter of which is 30 cm, and which is filled with hydrogen at a pressure of 8 atm.) the time dependence of R is the one shown in Fig. 4. As is shown by this plot, the asymptotic value of this ratio, of the order of 2%, is such to create a completely preponderant neutron background; to see this, it is sufficient to underline once more that the rate of reaction (1) is an effect of the order of 1/1000 in comparison to the muon decay (2), and to remember the huge values quoted for the nuclear capture rates in heavy elements (Table I).

The existence of the walls for the container seems to remove the possibility of performing the experiment also from another point of view. Let us suppose to set up the experiment on the lines of the one already quoted of the Columbia group: let the stopping of a muon be then defined (Fig. 5) by the coincidence signal of a telescope of counters (which defines the beam) and by the anticoincidences of a box of plastic scintillators A_i, which surround the container T, and are placed between the latter and the neutron counters N_i. In this case, also the muons stopping in the walls of the container are accepted as stopping in the target; but, in our case, the ratio between the latter and the number of those actually stopping in hydrogen is worsened by a factor close to 100, due to the decreased density of hydrogen; the acceptation of the muons stopping in the walls of T as if they were stopping in hydrogen would then imply to open the gate on the neutron

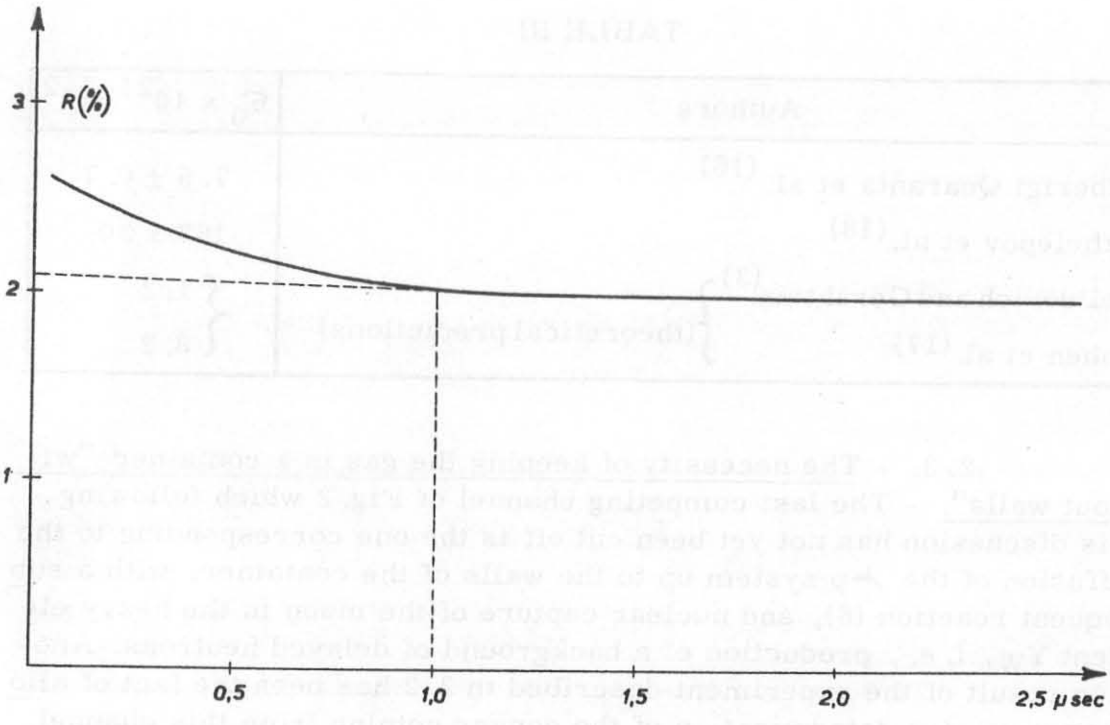

FIG. 4 - Time behaviour of
R = (number of muons transferred to the wall of the container after time t_o)/(number of muons decaying after time t_o).
The container is supposed to have a 30 cm diameter, and to be filled with pure hydrogen at a pressure of 8 abs. atm. ; muons are assumed to stop uniformely in the gas. (From ref. (19); figure reproduced with permission from Nuclear Instruments and Methods).

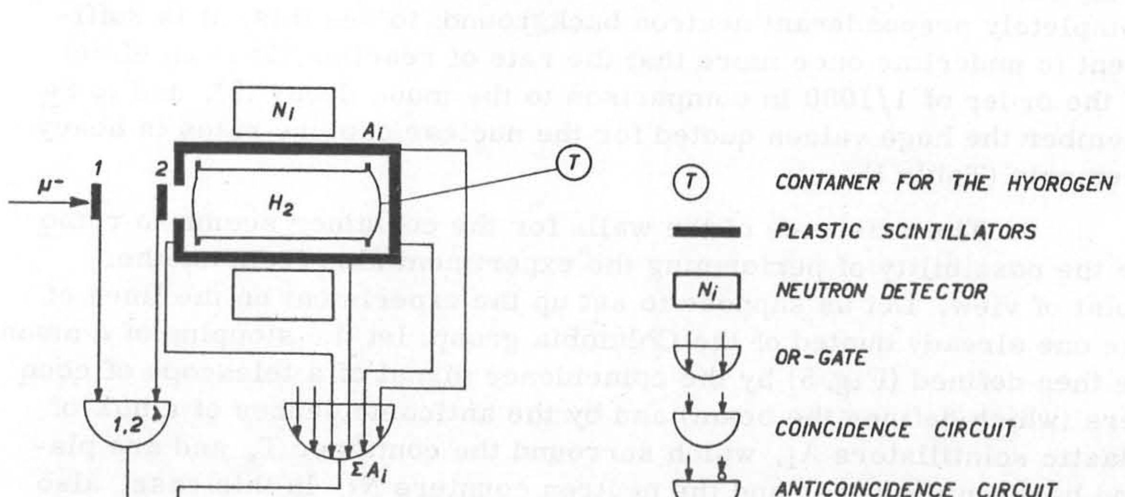

FIG. 5 - μ^- nuclear capture rate in gaseous hydrogen: a bad method to define the event: "a μ^- has stopped in hydrogen".

counters logic at such a large frequency that the accidental counts (even assuming that these are due only to the cosmic radiation) would constitute a prohibitive background.

To prosecute in setting up the experiment, therefore, it has been necessary to consider an avoidable matter the fact that the used container should be endowed with walls; and we have been led to conceive a device which ought to approximate the operation of a container without walls.

The scheme is the following: if one suceeds, by an electronic operation, in accepting as a μ^- stopping in hydrogen only those cases in which a muon has stopped in the gas at a distance from the walls larger than a sufficiently large distance d, the probability that the μp atom formed in these conditions may attain the walls before the decay (2) happens can be made very small; and, on the other hand, the frequency of the gate signals which "wait" for the neutron counters signals is reduced by a factor which takes it to proportions actually corresponding to the number of muons stopping in hydrogen.

These operation have been realized by introducing in the container a complex structure of thin wires, suitably grouped and conveniently polarized: the wires produce some electric fields similar to those due to a certain number of proportional counters, which work using the protonium itself as a filling gas. More precisely, as is shown in Fig. 6, the forementioned counters have been built as follows:

a) a peripheral counter (γ), which operates producing an anticoincidence signal for each muon which stops at a distance from the side wall of the container smaller than d = 4.5 cm (and in general in correspondence to any charged particle which crosses the d thickness);

b) a cylindrical counter (β) situated in the back of the container (with reference to the entrance of the muon beam), which has analogous anticoincidence functions connected to the back wall of the container. The effective thickness of β has been fixed with a view to compensating any "dead angles" in the assembly of these anticoincidence coun-

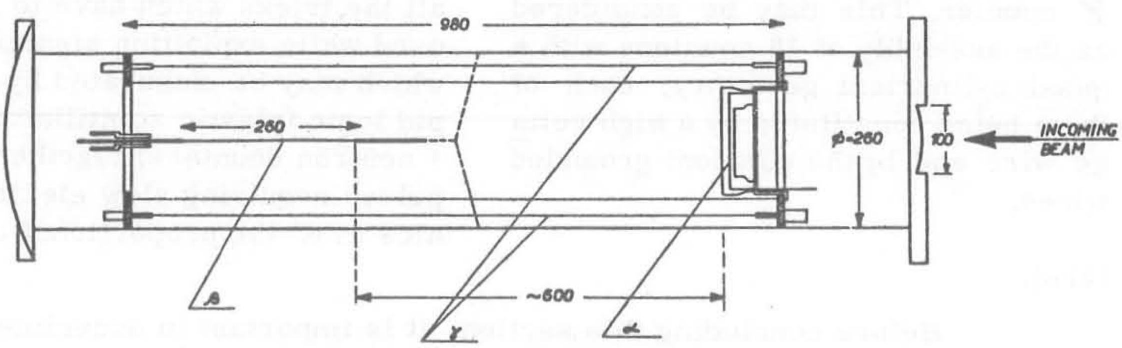

FIG. 6 - Overall scheme of the complex structure of proportional counters working inside the container for the protonium to transform it into a "target without walls".

ters, and so that the useful volume of the container might be in the neighborhood of the neutron counters N_i (see Fig. 10);

c) a fast grid counter (α) (i. e. a plane structure counter) placed close to the entrace flange of the container, and having coincidence functions.

An ($\alpha\bar{\beta}\bar{\gamma}$) signal can then be interpreted as if it were due to a muon which has entered the container, and has stopped in the useful region V which is limited only by the electric fields due to counters α, β, γ. But these fields (see for instance Fig. 7, which shows the section structure of counter γ) are generated by some extremely thin wires (the thickest ones have a 100 micron diameter) and not by a continuous wall; the original requirement that the gas should be contained in a V volume not limited by any material wall is therefore fulfilled. A calculation has shown that the background neutrons due to the transfer process of muons from μp atoms to the wires is less than 5% of the "true" effect.

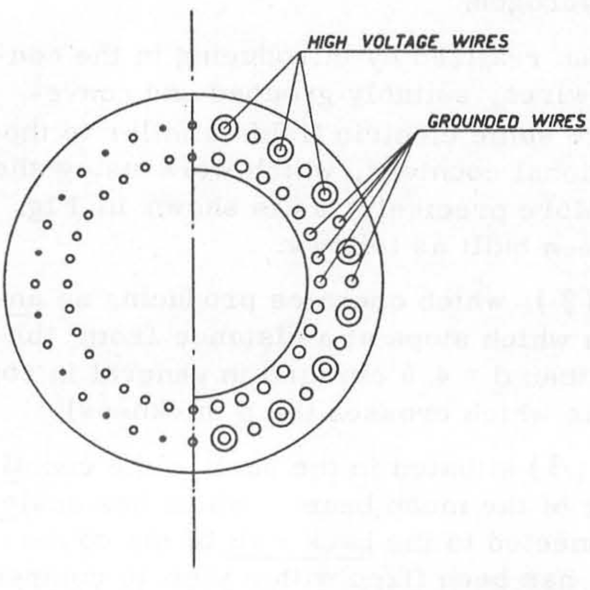

FIG. 7 - The disposition of the grounded and high voltage electrodes in the γ counter. This may be considered as the assembly of 16 counters with a quasi-cylindrical geometry, each of them being constituted by a high voltage wire and by the adjadent grounded wires.

The assembly of the proportional counters, and their working characteristics, are described in a paper by Alberigi Quaranta et al. [19]. In Table IV some of these parameters are given, since they seem significant to show the difficulty which one meets while using proportional counters under high pressure conditions. The high pressure requested a special care in the mechanical study of the components, to prevent the possibility of any type of electrostatic discharge; and the long collection times for the electrons (and their fluctuations) have imposed all the tricks which have to be used while exploiting signals which may be elaborated by a rapid logic (plastic scintillators + + neutron counters) together with pulses requiring slow electronics (i. e. the proportional counters).

Before concluding this section, it is important to underline that the device we constructed allows also a continuous control of the condition of purity for the filling gas. The operation of counter β, in fact, due to its huge effective volume, has shown to be critically conditioned by the purity of the protonium, in such a way that 20 p. p. m. of air, artificially in troduced into the container, cause a variation of the counts connected to β of the order of 6%. During the experiment, the protonium was substituted each day, and, before starting the runs, it had been observed that the counts connected to β (in full beam conditions) were stable within 0.5% over a period of 4 days.

TABLE IV

Counter	Protonium pressure (abs.atm.)	H.V. (kV)	Duration to which a signal has to be stretched if it has to be put in coincidence with the counter pulse (microsec.)
α	8	15	0.5
β	8	19	15
γ	8	8.2	15

On the other hand, due to the specific properties of xenon, the injection of a 1/1000 proportion of this gas, which has been foreseen in 2.1 for the determination of the delayed background of neutrons due to the presence of light materials(o), does not affect sensibly the operation of the counters, in such a way that the measurement discussed in that section can be performed in analogous conditions as in the data taking not only as to the number of muons stopped in hydrogen, but also as to the working conditions of the assembly of the proportional counters.

The setting up of this instrument, the prototype of which has been studied in this Institute, whereas its definitive model has been mounted at CERN, has certainly been the most delicate and critical phase of the preparation of the experiment, which on the other hand has been made possible only by the realization of this device.

3. - THE EXPERIMENT. -

Assuming that all the discussed competing processes (apart from react. (2), of course) have been eliminated by the methods cleared up in the preceeding section, the probability that in a mesic atom μp in the singlet state the nuclear capture (1) takes place is given by

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(o) - Light materials are mainly present in the container as insulating supports for the high voltage wires; these supports have been made of Teflon (PTFE) due to the dielectric and thermal properties (degassability) of this material.

(10) $$p = \frac{\lambda_s}{\lambda_s + \lambda_o} \cong \lambda_s / \lambda_o .$$

Furthermore, calling

$N_{\mu\, stop}$ the number of muons stopped in hydrogen;

N_n the corresponding number of neutrons due to process (1);

ε_n the efficiency of the system for detecting neutrons;

N_n' the number of counted neutrons;

N_{nf}' the number of counted neutrons which are due to any source except reaction (1);

Ω_n the total solid angle subtended by the neutron counters;

T the time cut factor due to the finite duration of the gate which interrogates the logic of the neutron counters,

one gets

(11) $$P = \frac{N_n}{N_{\mu\, stop}} = \frac{(N_n' - N_{nf}')}{\varepsilon_n \Omega_n T N_{\mu\, stop}}$$

Then

(12) $$\lambda_s = P\lambda_o = \frac{(N_n' - N_{nf}')\lambda_o}{\varepsilon_n \Omega_n T N_{\mu\, stop}} .$$

On the other hand, since, in the conditions under which we are supposed to work, practically each muon stopped in hydrogen decays according to (2), by counting the decay electrons (using the same assembly of counters engaged in the neutron countings) it is possible to infer the value of $N_{\mu\, stop}$; more precisely, if one calls

N_e' the number of detected electrons;

N_{ef}' the number of electrons due to muon decay in mesic atoms $\mu Y \neq \mu p$;

Ω_e the total solid angle under which the N_i counters see the electrons coming from the useful volume V of protonium;

ε_e the efficiency of the system to count electrons,

one gets

(13) $$N_{\mu\, stop} = \frac{(N_e' - N_{ef}')}{\varepsilon_e T \Omega_e} .$$

This method for the determination of the number of muons actually stopped in protonium is more reliable than the pure electronic counting, which is given (see Fig. 10) by the signal of a telescope of counters (1, 2, α) (see Fig. 10) that is anticoincided by the possible pulses of counters β and γ ; the reason of this fact is mainly due to the facility by which, in this condition, the electrons, detected by the same N_i are scaled under a solid angle similar to the one through which the neutrons are counted; furthermore, the electrons are accepted in the same time interval (fixed by the gate) which is imposed to the neutrons, i. e. the T factors are the same both in (12) and in (13). Substituting in (12) the expression (13) one obtains

$$\lambda_s = \frac{(N'_n - N'_n) \varepsilon_e \Omega_e}{(N'_e - N'_{ef}) \varepsilon_n \Omega_n} \quad . \tag{14}$$

Formula (14) expresses then the rate of reaction (1) as a function of the most convenient experimental data.

In what follows I will discuss shortly the apparatus built-up to get information on the variables which are in formula (14), and the general features of the data taking and of the data analysis.

3. 1. - The neutron detectors. - The detectors chosen to scale the emitted neutrons (and, in a separate measurement, the decay electrons) are of the same type of those used in the quoted experiment of the Columbia group; i. e. they are made by liquid organic scintillators(+), seen by photomultipliers. The advantage of this choice lies in the fact that these liquids can discriminate very efficiently between neutrons and gamma rays; and, in our experimental situation, the latter (due both to bremsstrahlung of the decay electrons in the walls of the container, and to the local background) may be even a factor 10 more numerous than the number of detected neutrons.

The technique of discrimination, developed by Brooks[20], is based on the difference in the pulse shape due to the two different kinds of radiations, which produce in the scintillator recoil protons (the neutrons) and electrons (gamma-rays). The scintillations processes due to protons and electrons, in fact, are governed by different time behaviour; this allows to insulate different time zones in any pulse, in such a way as to obtain, in correspondence to the particle which provoques it, two signals; of these, one (AN_i) has an amplitude corresponding to the energy of the particle whereas the other (CN_i) has an amplitude according to which one can infer which is the type of impinging particle. In Fig. 8,

(+) - NE 213 liquid scintillators, supplied by Nuclear Enterprises (G. B) Ltd., Sighthill, Edinburgh, Scotland.

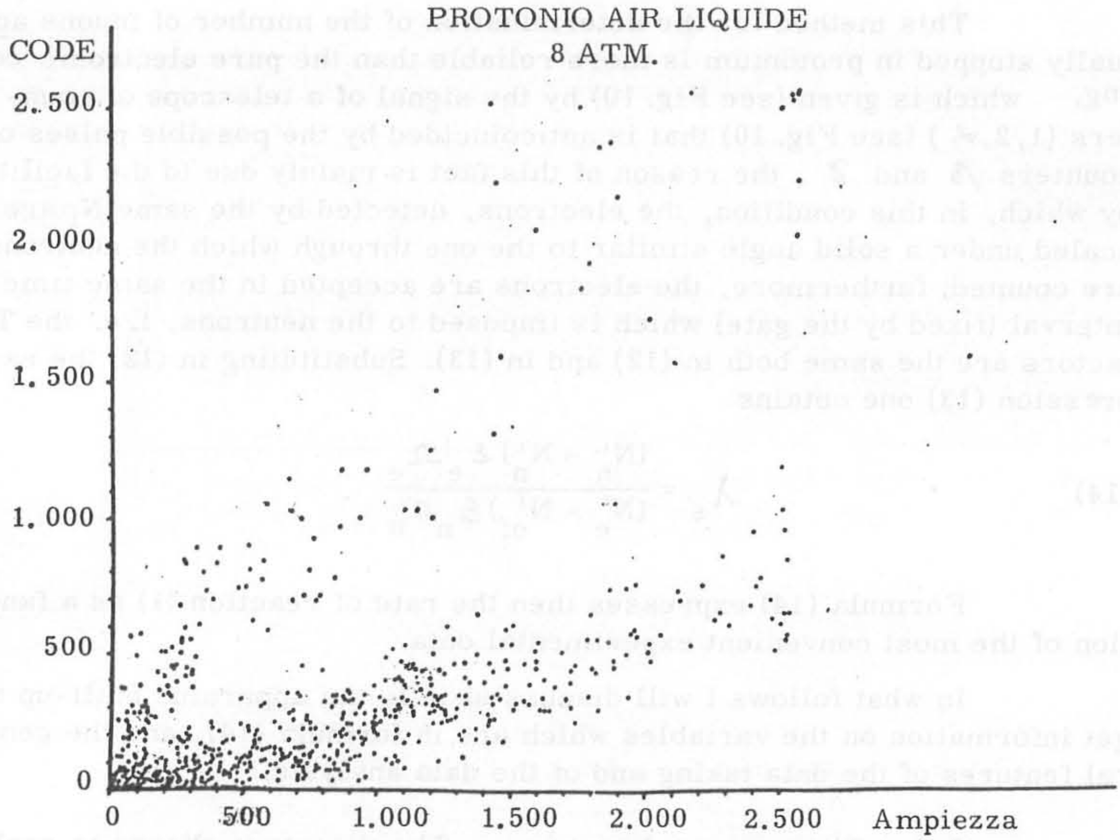

FIG. 8 - Distribution of pulses due to neutrons (upper band) and to gamma rays (lower band) in a typical plot of n - γ discrimination (Abscissae: AE_i; ordinates: CN_i).

were a certain number of events of the experiment are displaced, one sees that the pulses due to neutrons (upper band of points) result clearly resolved from those due to gamma rays (lower band) in an (AN_i, CN_i) plane.

The dimensions of our scintillators (Ø 18.46 cm, thickness 10 cm) are larger than those of the scintillators used in the Columbia experiment; the choice of the ne_w sizes has been determined by the necessity of subtending the maximum solid angle compatible with losses in the energy resolution (due to the increased probability of dissipations in the light collection). The expected resolution is about 20%, whereas the efficiency is around 30%.

Our technique of <u>pulse-shape discrimination</u> between neutrons and gamma rays is simplified in comparison to the one developed by Brooks, and it has been checked in some measurements; these measurements have been performed on the μ-channel of the 600 MeV CERN Synchrocyclotron, with a view to determining the rates λ_{cY} of nuclear capture for negative muons in some elements Y (solid targets). The determination of λ_{cY} has been reduced to the measurement of the time distribution of the neutrons delayed in comparison to the arrival of the muons in the target; the lifetime τ of this distribution is actually given by the relation

$$1/\tau = \lambda_{cY} + \lambda_{dY} \tag{15}$$

(see Fig. 1), where λ_{dY} is the rate at which process (2) proceeds in the mesic atom μY[21]; the λ_{cY} value are then calculated from the known values of λ_{dY} and τ.

The technique used in these measurements[22] is different from the one followed by other teams[23, 24] for the determination of the λ_{cY} rates in some of the considered elements. These authors defined in fact the μ^- stopping in the target by a coincidence-anticoincidence signal of plastic scintillators (1,2,3, $\overline{\Sigma A_i}$), where as usual counters 1, 2 and 3 constituted a telescope which was defining the incoming beam, whereas the anticoincidence counters A_i, encircling the target, (except from the entrance side)was supposed to guarantee that the muon had actually stopped in it. In our measurements, the μ^- stopping in the target was defined by the further requirement that a NaI scintillator should detect, in coincidence to the(1,2,3, $\overline{\Sigma A_i}$) pulse, a gamma ray, the energy of which had to correspond to a specific transition of the μY atom to its ground state. In this way it was certain that the mesic atom which was of interest had actually been formed, and the measurement was free from the systematic error due to the stopping of muons in the light elements present in plastic scintillators, the accidental counts being then strongly reduced.

The results of these measurements(o) are given in Table V, where they are compared to the data obtained by other groups. The values obtained by us are extracted from low-statistics data, and they have not been enriched because the aim of the measurements was mainly that of checking the operation of the new pulse-shape discrimination logic. In Fig. 9 our results are compared with the theoretical curve due to Primakoff[2] for the dependence of λ_{cY} from the atomic number Z of the capturing nucleus.

3.2. - <u>The experimental set-up and the electronics.</u> - The experimental apparatus, mounted on the μ-channel of the Synchrocyclotron, is sketched in Fig. 10. The low energy muon beam (momentum around 100 MeV/c) is collimated, and defined by the coincidence of two plastic scintillators # 1 and # 2. A properly thick beryllium moderator is set on the beam trajectory, in order to reduce the energy of the particles to such values that they can stop in the useful volume V of gaseous hydrogen; the moderator has furthermore been placed inside the container to reduce losses due to multiple scattering in beryllium.

The V volume is seen by four neutron detectors N_i, symme-

(o) - These data are unpublished.

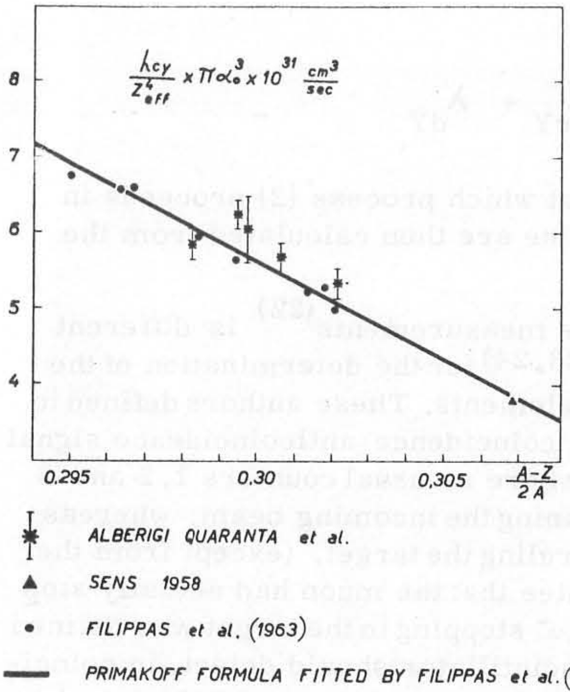

FIG. 9 - Comparison of the theoretical plot, due to Primakoff, expressing the behaviour of λ_{cY} as a function of the characteristics of the Y nucleus, with the available experimental datas. a_o is the Bohr radius for the muon.

trically disposed around it, their axis being normal to the axis of the container; each N_i counter is inserted in a cavity prepared in lead blocks as thick as 20 cm, which are also protected by a 50 cm thick paraffing wall, to get a shield against gamma rays and low energy neutrons respectively.

Between each N_i counter and the container a plastic scintillator A_i is enclosed, of such dimensions that any particle leaving V and impinging on N_i has to cross A_i too, which on the other hand detects it with good efficiency only if the particle is a charged one.

A very simplified scheme of the electronics is shown in Fig. 11; in what follows I shall briefly discuss it, keeping in mind that the main function of this system was to supply a signal which commands the data recording only in correspondence of an event which is worth while being analyzed. This operation is developed through the following steps:

TABLE V

Element	Nuclear capture rate $\lambda_{cY} \times 10^6 xec^{-1}$		
	Alberigi Quaranta et al.[22]	Filippas et al.[23]	Sens[24]
W	12. 86 ± 0. 45	---	11.92 + 0.30
Au	14. 87 ± 0. 48	13. 39 ± 0. 11	---
Ir	12. 93 ± 0. 99	---	---
Hg	14. 23 ± 0. 44	---	---
Pb	13. 90 ± 0. 59	12. 98 ± 0. 10	11.70 ± 0.75

1) definition of the event: " a μ^- has stopped in hydrogen" (μ^- -stop), which is performed in this way:

- the beam of the incoming particles, which is controlled by the MONITOR fast coincidence, as it has been mentioned, (MONITOR = (1, 2)), is defined with a better precision in connection to the V volume by the MASTER coincidence (MASTER = 1, 2, $\Sigma \overline{A}_i$, α), which is still rather fast, since the α counter has time fluctuations included within 500 nanosec (see Table IV).

- The output of the MASTER coincidence is put in slow anticoincidence with the mixed pulses coming from counters β and γ, the response of which has time fluctuations included (in 90% of the cases) within 15 microsec (see Table IV); this operation is done in the μ - STOP coincidence (μ^- - STOP = 1, 2, $\Sigma \overline{A}_i$, α , $\overline{\beta}$, $\overline{\gamma}$).

The logic contains further complications which have the function of letting only those muons of the beam which are neither preceded, nor

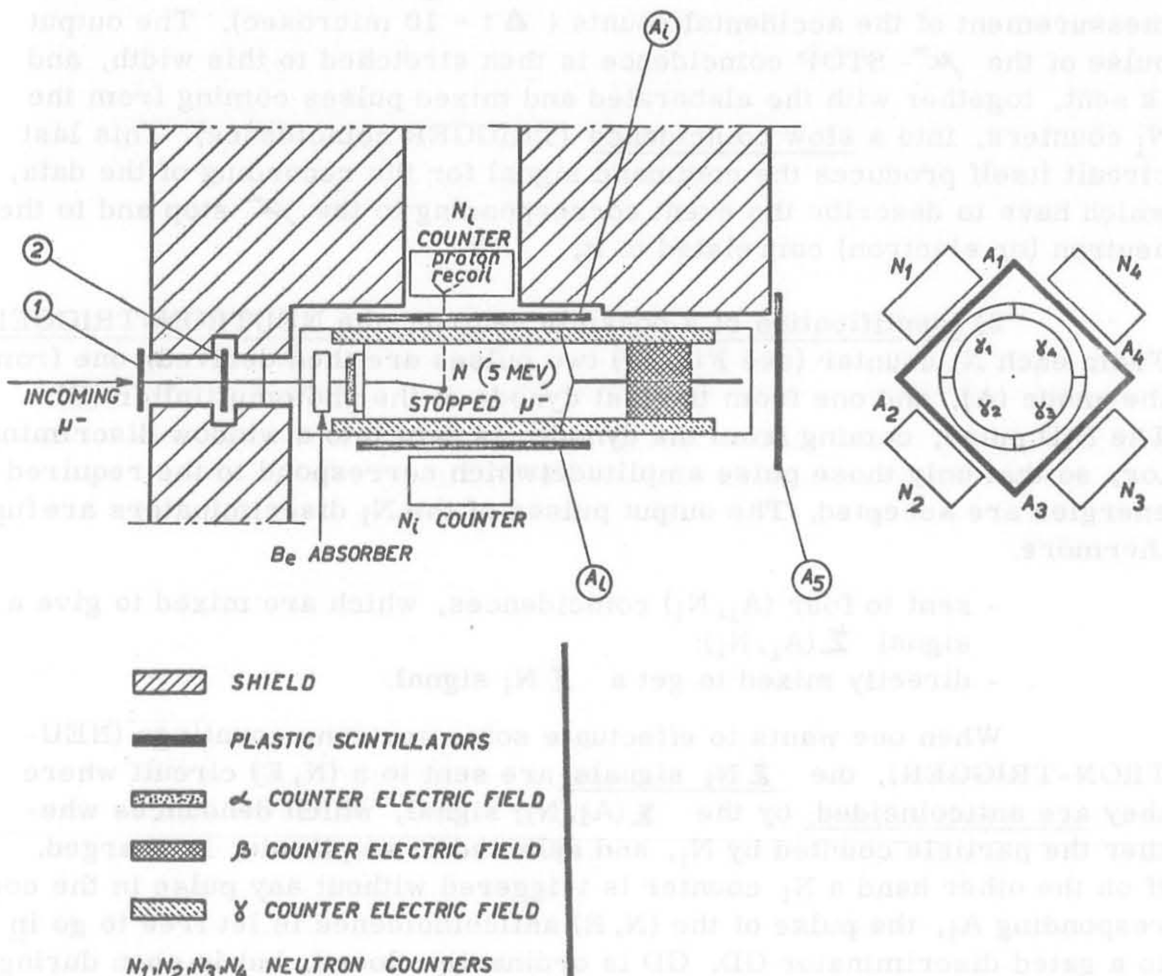

FIG. 10 - μ^- nuclear capture rate in gaseous hydrogen; scheme of the apparatus. (From ref. (19); reproduced with permission from Nuclear Instruments and Methods).

followed by another muon within a time interval of ± 10 microsec) to be accepted for further operation. The beam crossing the (1, 2) telescope is of about 8 10^3 particles/sec, and the duty cycle of the machine is about 40% in the conditions of the measurements. The μ^- - STOP coincidence scales correspondingly 15 - 20 counts/sec. In Fig. 11 all the delay lines necessary to perform the coincidences are not shown; furthermore, all the logic connected with the shaping of the pulses coming from the various detectors, which was of special importance mainly for the counters α, β, and γ, is neglected.

The μ^--STOP anticoincidence would then supply a signal corresponding to the stopping of an incoming negative muon in the protonium contained in the V volume. The following operation is that of interrogating, for a fixed time interval Δ t, the logic connected to the pulses of the neutron detectors; Δ t has been fixed keeping in mind the mean life time of the muons, and it has been chosen long enough to allow a good measurement of the accidental counts (Δ t = 10 microsec). The output pulse of the μ^-- STOP coincidence is then stretched to this width, and is sent, together with the elaborated and mixed pulses coming from the N_i counters, into a slow coincidence (TRIGGER coincidence). This last circuit itself produces the command signal for the recording of the data, which have to describe the event corresponding to the μ^- stop and to the neutron (or electron) correlated to it;

2) identification of a possible neutron: the NEUTRON-TRIGGER. From each N_i counter (see Fig. 11) two pulses are then derived, one from the anode (A), and one from the last dynode of the photomultiplier (D). The N_iD pulse, coming from the dynode, is sent into a window discriminator, so that only those pulse amplitudes which correspond to the required energies are accepted. The output pulses of the N_i discriminators are furthermore.

- sent to four (A_i, N_i) coincidences, which are mixed to give a signal $\Sigma(A_i, N_i)$;
- directly mixed to get a ΣN_i signal.

When one wants to effectuate some neutrons countings (NEUTRON-TRIGGER), the ΣN_i signals are sent to a (N, E) circuit where they are anticoincided by the $\Sigma(A_i, N_i)$ signal, which denounces whether the particle counted by N_i, and selected in amplitude, is charged. If on the other hand a N_i counter is triggered without any pulse in the corresponding A_i, the pulse of the (N, E) anticoincidence is let free to go into a gated discriminator GD. GD is ordinarily closed, but is open during the whole width of a gate signal coming from the MASTER coincidence, which should last 10 microsec, unless it is shut before by

- any of the A_i giving a pulse before the arrival of the neutron;
- the neutron itself immediately after its passage.

In this case then, a signal of the TRIGGER coincidence means

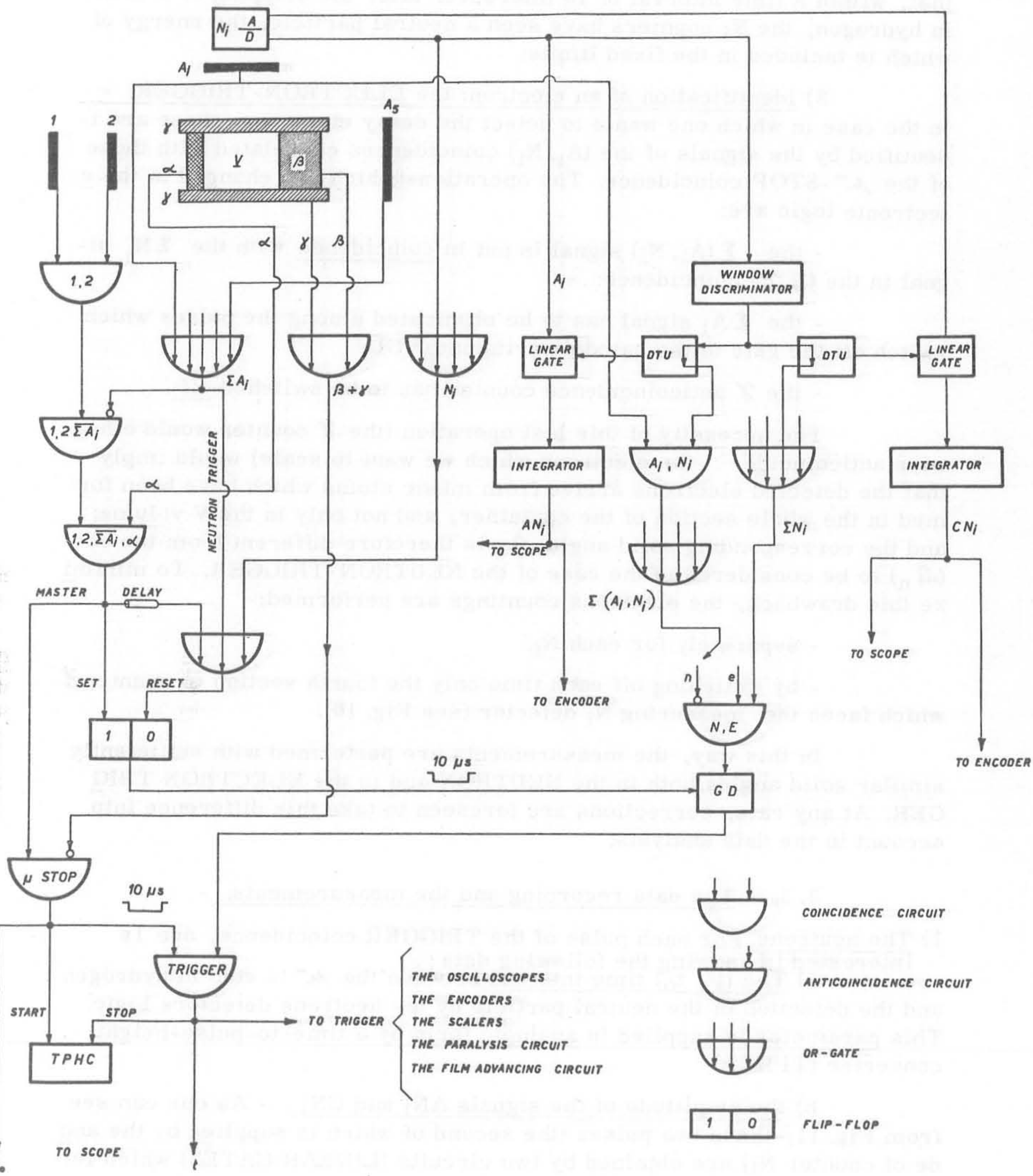

FIG. 11 - μ^- nuclear capture rate in gaseous hydrogen: simplified scheme of the electronics.

that, within a time interval of 10 microsec. after the stopping of a muon in hydrogen, the N_i counters have seen a neutral particle, the energy of which is included in the fixed limits;

3) identification of an electron: the ELECTRON-TRIGGER. - In the case in which one wants to detect the decay electrons, these are identified by the signals of the (A_i, N_i) coincidences correlated with those of the μ^--STOP coincidence. The operations which are changed in the electronic logic are:

- the $\Sigma(A_i, N_i)$ signal is put in coincidence with the ΣN_i signal in the (N, E) coincidence;

- the ΣA_i signal has to be eliminated among the pulses which switch off the gate to the gated discriminator GD;

- the γ anticoincidence counter has to be switched off.

The necessity of this last operation (the γ counter would otherwise anticoincide the electrons which we want to scale) would imply that the detected electrons arrive from mesic atoms which have been formed in the whole section of the container, and not only in the V volume; and the corresponding solid angle Ω_e is therefore different from the one (Ω_n) to be considered in the case of the NEUTRON-TRIGGER. To minimize this drawback, the electrons countings are performed:

- separately for each N_i;

- by switching off each time only the fourth section of counter γ which faces the measuring N_i detector (see Fig. 10).

In this way, the measurements are performed with sufficiently similar solid angles both in the NEUTRON and in the ELECTRON TRIGGER. At any rate, corrections are foreseen to take this difference into account in the data analysis.

3. 3. - The data recording and the measurements. -

1) The neutrons. For each pulse of the TRIGGER coincidence, one is interested in knowing the following data:

a) The $(t - t_0)$ time interval between the μ^-'s stop in hydrogen and the detection of the neutral particle by the neutrons detectors logic. This parameter is supplied in analogic form by a time-to-pulse-height converter (TPHC);

b) the amplitude of the signals AN_i and CN_i. - As one can see from Fig. 11, these two pulses (the second of which is supplied by the anode of counter N_i) are obtained by two circuits (LINEAR GATES) which let to pass only that fraction of the input signal which is coincided by an opening gate, coming from a DELAYED TRIGGER UNIT (DTU). By differently adjusting the delay and the widths of the pulses of the two DTU, one succeds in obtaining discrimination figures as the one shown in Fig. 8;

c) which of the N_i counters has given the signal;

d) <u>information on the stability of the apparatus.</u>

These information are supplied in digitized form by the print of the SCALERS, which count:

- the output pulses of the main coincidence and anticoincidence circuits;

- the output pulses of three analog-to-digital converter (ENCODER), which transform in pulse trains, the length of which is proportional to the amplitude of the input pulse, the signals forementioned in a) and b);

- the output pulse of an auxiliary circuit, not shown in Fig. 11, which supplies a code number for each N_i counter.

For each TRIGGER, moreover, the following pulses are displayed on four oscilloscope tracks, seen by a camera:

- any pulse coming from the γ counter (first track) and from the β counter (second track) within a time interval of 40 microsec. after and 10 microsec. before the t_o time defined by the μ^--STOP coincidence. The latter circuit covers actually only a 15 microsec. interval (see Table IV), in order not to introduce too big losses in the acceptance of the incoming beam (remember that any frequency of incoming muons lower than 1 part/10 microsec is acceptable). The recording on the film of the β and γ signals with these time limits allows a further selection of the events defined as μ^-'s stopping in hydrogen, in such a way that the inefficiency of the β and γ anticoincidences is actually reduced to less than 1%;

- the signal coming from the μ^--STOP coincidence, and the one produced by the TRIGGER coincidence, correlated with the former (third track); the measurement of the distance between these signals on the track allows a control of the measurement of the times $(t - t_o)$ and also of the stability of the TPHC and of the ENCODERS;

- the two signals CN_i and AN_i (fourth track) with analogous auxiliary functions.

The signal coming from the TRIGGER coincidence cuts off an electronic paralysis which is normally blocking the ENCODERS and the SCALERS connected to these; furthermore, it triggers the motor which has to bring forward the impressed film, and the data printing system. Immediately afterwards, the measurements re-begins.

An event recorded during a NEUTRON-TRIGGER measurement is described by a series of numbers (digitized outputs of the data), to which a photograph of the oscilloscope tracks is associated (analogic form of the data output); the photograph of a "good" event is shown in Fig. 12.

2) <u>The electrons.</u> - During the electrons measurements, no interest is attached to the data corresponding to the CN_i and AN_i pulses;

and the importance of the anticoincidences β and γ is much reduced. For any ELECTRON-TRIGGER event one is then led to print only the TPHC output and the most necessary data which control the stability of the apparatus. In such a way a factor 5 is gained in the time required for the measurement.

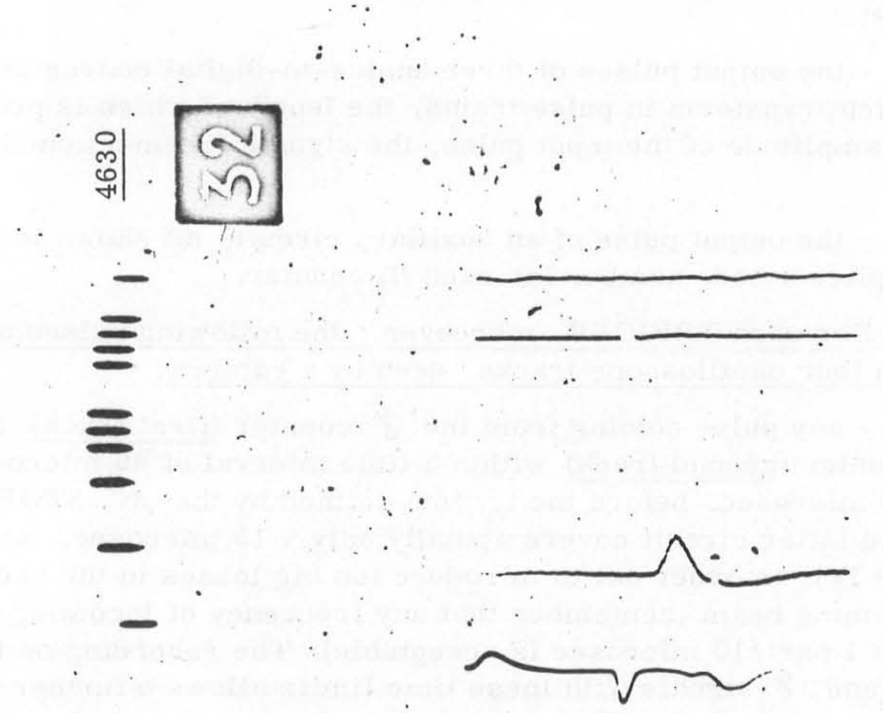

FIG. 12 - μ^- nuclear capture rate in gaseous hydrogen: photogram of an event. In the figure four oscilloscope tracks, are displayed; the upper ones, (apart from an emply space in the second track, which corresponds to a pulse of time reference) are empty, thus meaning that no anticoincidence pulse from the β and γ counters are present. On the left of the figure, some numbers are visible, which give the order number of the event and the number of the film over which the photogram is found. At each photogram a digitized description of the event is also associated.

In conclusion, and remembering what has been told in sect. 2.1 and 2.3 on the measurement of the background neutrons (and, correspondingly, of the background electrons) scaled by the apparatus, and coming from mesic atoms differing from the μp systems, the main foreseen and performed measurements on the parameters of formula (14) are listed in Table VI. It has to be underlined that, whereas the pure electronic counting directly supplies the N'_e and N'_{ef} numbers, it is only by the analysis of the collected events that one is able to arrive to the determination of the corresponding N'_n and N'_{nf} of Table VI.

TABLE VI

Filling gas	TRIGGER	Obtained datum
Pure Protonium (8 abs. atm.)	NEUTRON	N'_n
	ELECTRON	N'_e
Protonium (8 abs. atm.) + 1°/oo Xe	NEUTRON	N'_{nf}
	ELECTRON	N'_{ef}

3.4. - The data analysis.-

1) - The recognition of the "good" events. - During the neutrons measurements, about 6000 events of the form of the one in Fig. 12 have been collected. Their acceptation as events of the N'_n (or N'_{nf}) category is established through the following steps:

- for each neutron detector, and for every measurement, the AN_i and CN_i pulses of all the events are collected in n - γ plots of the type of the one in Fig. 8;

- all the events the photograms of which show some pulses on the tracks reserved to the β and γ anticoincidences, within proper limits are rejected. This selection reduces the number of events by a factor of the order of 3;

- for each still acceptable event, the position of its (AN_i, CN_i) point is examined on the n - γ plot of the considered measurement, and the event is rejected if the point falls within the zone reserved to gamma--rays; this selection reduces the number of photograms by a factor close to 7.

On these "true" neutrons two more discriminations are operated:

- in time: only those events for which the $(t - t_o)$ time is bigger than 0.6 microsec. are accepted, to eliminate the residual counts of neutrons due to those μ^- directly stopping in high-Z materials surrounding the V volume;

- in energy : only those neutrons which give pulses of amplitude corresponding to energies larger than 1 MeV are accepted. It is useful to remember now that the neutrons coming from (1) have a fixed energy (5.2 MeV), but that the distribution of the recoil protons extends down to low energies; to this phenomenon another loss in monocromaticity is added by the fact that the neutrons, before arriving on the N_i detectors, may scatter against hydrogen, the walls of the container, the plastic scintillators A_i, the glass containing the liquid scintillator, etc.

The picture we have drawn of the measurements executed on the collected datas are necessarily a quite schematic one; the analysis is made of many other checks and measurements, which we omit here for sake of brevity.

2) - The evaluation of the efficiencies and of the solid angles. - To evaluate the ε_n, Ω_n, ε_e, Ω_e parameters which are in formula (14), one has to rely on calculations, which are made more complicate by the fact that the particular source of neutrons (electrons) which we face here is not a point-like source, but a diffused one ($\equiv$ V volume). This implies that:

- the solid angles may be evaluated only when the spatial distribution of the muons stopped in V is known;

- the pulses in the neutron detectors N_i depend on the direction of incidence;

- as has been told in 1), the energies of the emitted neutrons degrade before they attain the N_i detectors.

It has therefore been necessary to calculate these parameters mainly by a computation, performed by a Montecarlo Method, which keeps account of the following facts:

- the cross sections for the neutrons vary with the energy;

- the scintillator liquid contains carbon besides hydrogen;

- the geometry of the N_i counters is such that the incoming neutrons may overcome multiple scatterings;

- the response of the detectors is not linear at the energies we consider.

This phase of the data analysis is the most critical one, both owing to the difficulties of the computation, and because the result of the measurement (and its error) depends directly on the value assumed for the efficiencies and the solid angles.

The data analysis is proceeding[(o)]. We hope to be able to relay at least 400 counts of neutrons actually coming from reaction (1).

(o) - The preliminary results of the experiment have recently appeared on Physics Letters [(24 bis)].

4. - APPENDIX. -

In what follows, some elements of the theoretical frame within which reaction (1) is currently discussed are given; the reader may find a thorough discussion in the literature(2, 4, 5, 25, 26).

The prediction for the nuclear capture rate for reaction (1) is obtained starting from a matrix element of the type

$$M \sim g_V \bar{U}_\nu \gamma_\mu (1 + \gamma_5) \bar{U}_\mu (\bar{U}_n \gamma_\mu U_p) + \tag{16}$$
$$+ g_A \bar{U}_\nu \gamma_\mu \gamma_5 (1 + \gamma_5) U_\mu (\bar{U}_n \gamma_\mu \gamma_5 U_p) + \text{h. c.}$$

where g_V and g_A are the vector and axial coupling constants respectively, γ_μ (μ = 1, 2, 3, 4) and γ_5 are the Dirac matrices, and U_i is the wave function for the $\underline{i}$ - th particle.

In the non-relativistic limit, formula (16) reduces to

$$M \sim g_V + g_A \langle \sigma_\mu \cdot \sigma_p \rangle . \tag{17}$$

Remembering that

$$\langle \sigma_\mu \cdot \sigma_p \rangle = \begin{cases} -3/4 \text{ if the } \mu p \text{ system is in the singlet state.} \\ 1/4 \text{ if the } \mu p \text{ system is in the triplet state.} \end{cases}$$

it is easy to notice that the strong dependence of the interaction from the hyperfine structure state is already present in equation (17). However, before being used to compute the transition probability, the matrix element has to be renormalized, to take in account the fact that, in process (1), also particles with a strong structure are present. The consequent modifications have been evaluated by Primakoff, which has obtained a matrix element of the type

$$M \sim G_V + G_A (\sigma_\mu \cdot \sigma_p) - G_p \langle (\sigma_\mu . k) \rangle \langle (\sigma_p . k) \rangle \tag{18}$$

where k is the neutrino momentum, and, if M is the proton mass, and μ_p and μ_n the magnetic moments of the proton and of the neutron respectively,

$$G_V = g_V^\mu (1 + k/2M)$$
$$G_A = g_A^\mu - g_V^\mu (1 + \mu_p - \mu_n) k/2M \tag{19}$$
$$G_P = (g_p^\mu - g_A^\mu - g_V^\mu (1 + \mu_p - \mu_n)) \, k/2M.$$

Due to the renormalization effects, then, the bare coupling constants appear to be replaced by form factors, which are functions of the quadrimomentum transfer; in particular, the possibility of intermediate one-pion states implies the presence of the pseudoscalar induced coupling g_p, whereas the $(\mu_p - \mu_n)$ terms (weak magnetism terms) are due to intermediate two-pion states. The theory foresees, moreover, that

(20) $$g_p^{\mu} = 7\, g_A^{\mu}.$$

By connecting the g_A^{μ} and g_V^{μ} constants to the corresponding coupling constants for β decay, one gets the following expression for the nuclear capture rate for process (1):

(21) $$\lambda = \frac{(a + b \langle \sigma_{\mu} \cdot \sigma_p \rangle)\, 158}{((g_V^{\beta})^2 + 3(g_A^{\beta})^2)} \sec^{-1}$$

where

(22) $$a = G_V^2 + 3G_A^2 + G_p^2 - 2G_A G_p$$

(23) $$b = 2(G_V G_A - 1/3\, G_V G_p) - 2(G_A^2 - 2/3\, G_A G_p).$$

Formula (21) leads to the predictions for the λ_s and λ_t parameters which the experimentalists have to verify. It has been deduced by the following assumptions:

1) L - invariance of the theory;

2) CP - invariance;

3) Locality of the interaction for the leptonic particles;

4) Complete muon-electron symmetry;

5) Universality of the Fermi interaction;

6) V-A form of the interaction;

7) Conserved muonic number.

From equation (21), and since the g_V^{β} and g_A^{β} constants are sufficiently well known, it is clear that a measurement of λ, besides being a test of the validity of the assumptions 1)-7), leads to a measurement of g_p, a constant over which one has not yet cleared up one's ideas. The experiments performed up to date on nuclei of different size[25] give discrepant values for g_p, and the reasons for these discrepancies are not at all clarified.

In the experiment we execut ed, the nuclear capture reaction (1) was observed in the singlet state of the hyperfine structure for the μp system. This will yield a value of g_p with an error of the order of 20%. A most favourable situation would be realized for this purpose if one could observe reaction (1) proceeding from the triplet state: in such conditions, in fact, it is easy to see that the matrix element (18) is mainly due to the pseudoscalar coupling.

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